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THE BAIKAL NEUTRINO TELESCOPE – RESULTS AND PLANS

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for the BAIKAL COLLABORATION

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New results from the Baikal neutrino telescope NT200, based on the first 5 years of operation (1998–2003), are presented. We derive an all-flavor limit on the diffuse flux of astrophysical neutrinos between 20 TeV and 50 PeV, extract an enlarged sample of high energy muon neutrino events, and obtain limits on the flux of high energy atmospheric muons. In 2005, the upgraded telescope NT200+ will be commissioned: 3 additional distant strings with only 12 photo-multipliers each will rise the effective volume to 20 Mton at 10 PeV for this largest running neutrino telescope in the Northern hemisphere.

Keywords: neutrino astronomy; neutrino telescope; exotic muons; BAIKAL.

1. The Detector NT200

The Cherenkov neutrino telescope is located in Lake Baikal, Siberia, at a depth of 1.1 km. The present stage of the Baikal telescope, NT200, was put into operation in April, 1998. It consists of 192 optical modules (OMs), mounted on 8 vertical strings, each with 24 pairwise arranged OMs – altogether forming a cylinder of 40 m diameter and 72 m height.[1]

Each OM contains a 37-cm diameter photo multiplier (PM). The two PMs of a pair define a *channel*. They are switched in coincidence in order to suppress background from bioluminescence and PM noise. A *trigger* is formed by the requirement of $\geq N$ *hits* (with

hit referring to a channel) within 500 ns. N is typically set to 3 or 4. For each event, amplitude and time of all fired channels are digitized and sent to shore. A separate *monopole trigger* searches for hit patterns characteristic for non- relativistic, bright objects like GUT monopoles ($\beta \sim 10^{-5} - 10^{-3}$).

Lake Baikal deep water has an absorption length of $L_{\rm abs}(480~{\rm nm}) = 20 \div 24~{\rm m}$, a scattering length of $L_s = 15 \div 70~{\rm m}$ and a strongly forward peaked scattering.

We present selected results from the first five years of NT200 operation (April 1998 – February 2003; 1038 livetime days). We focus on the atmospheric muon neutrino sample, the diffuse high energy neutrino flux and on high energy atmospheric muons. For results on Magnetic Monopoles, WIMPs and GRBs see Ref. 2. We describe the upgraded telescope NT$200+$, to be commissioned in spring 2005.

2. Atmospheric Muon Neutrinos

The signature of charged current muon neutrino events is a muon crossing the detector from below. Muon track reconstruction algorithms and background rejection have been described elsewhere.[3] The analysis of the full 5-years sample re-optimizes for higher signal passing rate, allowing for a contamination of $15 - 20\%$ fake events.

A total of 372 upward going neutrino events are found. The arrival direction distribution for this preliminary sample (skyplot in galactic coordinates) is given in Fig. 1. Monte-Carlo simulations predict a total of 385 atmospheric neutrino and background events, with an energy threshold of $15 - 20$ GeV.

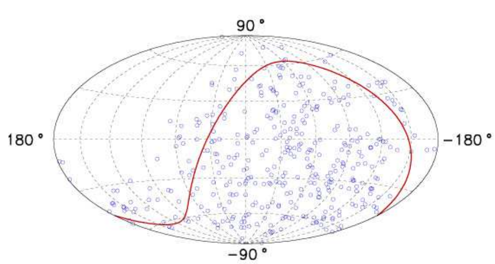

Fig. 1. Skyplot of neutrino events (galactic coordinates) for five years.

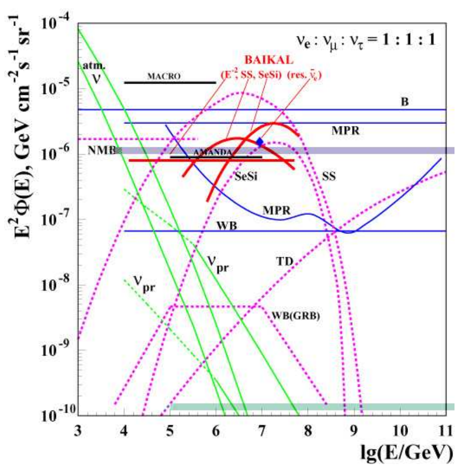

Fig. 2. Limits on diffuse neutrino flux from this analysis (Baikal), compared to other experiments, theoretical bounds and model predictions.

3. Search for Extraterrestrial High Energy Neutrinos

The sensitivity of NT200 is maximal for ν_e and ν_τ interactions (charged and neutral current) and ν_μ neutral current interactions – when bright electromagnetic and/or hadronic cascades are formed at the interaction vertex. For these "cascade events", light from the pointlike cascades is visible from large distances. For vertices located far outside the telescope sufficient background rejection power is retained against the main background – bright bremsstrahlung flashes along downgoing atmospheric muons passing far outside the array.[4] Key point is the low level of light scattering in Baikal water, resulting in a sensitive volume significantly exceeding the geometric detector volume. This yields a sensitivity of NT200 comparable to the much larger AMANDA detector.

The data analysis is essentially unchanged with respect to the detailed description for earlier data samples.[2,4] It selects events with (1) the minimum time difference of all combinations of hit channels along each string, $t_{\rm min}$, compatible with an upgoing plane light wave, and (2) a large number of hit channels in the detector $N_{\rm hit}$ (used as rough energy measure). For 1038 lifetime days, in total 3.45×10^8 events with $N_{\rm hit} \geq 4$ have been recorded. The distribution of selected cascade events is compatible with the background from bright high energy muons.[2,4] From the absence of any events in the signal region (i.e. with large $N_{\rm hit}$), an upper limit on the diffuse flux of extraterrestrial neutrinos of a given spectrum is derived. The effective volume rises from 2×10^5 m^3 for 10 TeV to 6×10^6 m^3 at 10^4 TeV – compared to a NT200 geometric volume of only $\approx 10^5$ m^3.

For an E^{-2} behaviour of the neutrino spectrum and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at earth, the 90% C.L. upper limit obtained in this analysis is:

$$E^2 \Phi_{(\nu_e + \nu_\mu + \nu_\tau)} < 8.1 \times 10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}. \tag{1}$$

The model independent limit on $\bar{\nu}_e$ at the W-resonance energy is:

$$\Phi_{\bar{\nu}_e} \leq 3.3 \times 10^{-20}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}. \tag{2}$$

Figure 2 shows our upper limits on ($\nu_e + \nu_\mu + \nu_\tau$) diffuse fluxes from AGNs shaped according to the models of Stecker and Salamon (SS), of Semikoz and Sigl (SeSi) and on an E^{-2} spectrum according to Nellen *et al.* (NMB) (experiment – solid, model – dashed lines; for references to diffuse models asee Ref. 2). The resonant $\bar{\nu}_e$ flux limit (2) is also shown (diamond). In addition, Fig. 2 gives experimental limits from MACRO[5] and the AMANDA-II cascade search,[6] theoretical bounds obtained by Berezinsky (B), by Waxman and Bahcall (WB), by Mannheim *et al.* (MPR), and predictions for neutrinos from topological defects (TD) and from GRB (WB(GRB)) [see Ref. 2 for the detailed references].

4. Search for High Energy Muons

Atmospheric muons and neutrinos are the most severe background source, when searching for extraterrestrial neutrinos. At GeV–TeV energy scale, atmospheric muons are predominantly produced in π/K-decays, with a well known steep power-law spectrum. Above the 10 TeV scale, the predicted energy spectrum is subjected to large uncertainties: "prompt"

muons with a harder spectrum and produced in semileptonic decays of charmed particles, are expected to dominate over the "conventional" π/K-muons. With heavy-quark production properties at these energies unknown, atmospheric muon flux measurements are needed.

To search for high energy muons, we use the same event sample and cuts as for the diffuse high energy neutrino sample, to which atmospheric muons in turn are a background source (see above). With no events left at final cut level, upper flux limits can be derived for various muon energy spectra. The experimental limit for a typical prompt muon spectrum with $\gamma = 2.7$, given in Fig. 3, is still above theoretical predictions.[2,7,8]

We can also test for an "exotic" component of high energy atmospheric muons, postulated[9] to explain the "knee" in the cosmic ray energy spectrum by a new interaction at PeV-scale.[10] The hard exotic spectra[9] (dashed curves in Fig. 3) result in a high sensitivity of NT200. Our experimental limit[11] for a generic E^{-2}-spectrum is given in Fig. 3. It shows, that the sensitivity is close to the lowest exotic flux.

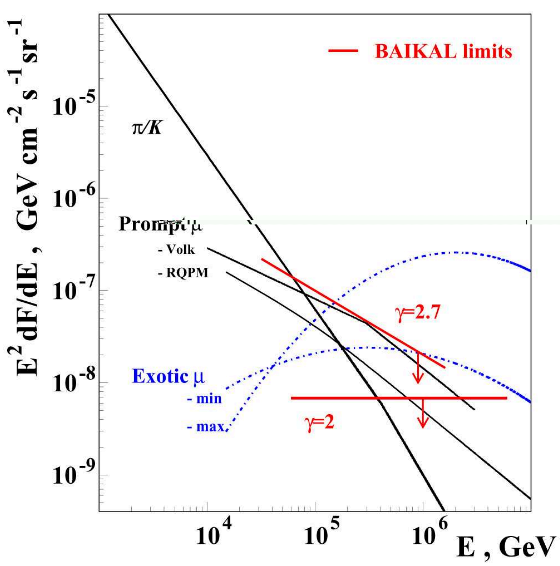

Fig. 3. Obtained upper limits on the high energy atmospheric muon flux (curves with arrows for $\gamma = 2$; 2.7), and predicted fluxes (for π/K, prompt, exotic).

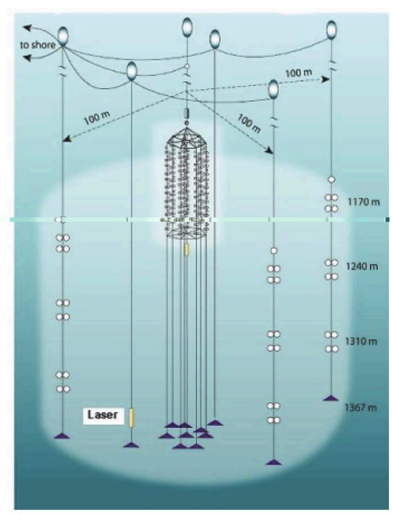

Fig. 4. Sketch of the new NT200+ telescope: with NT200 at center, and 3 new outer strings at 100 m radius.

5. The Upgraded Telescope NT200+

To reach a significant sensitivity improvement for high energy cascade neutrino events, we are upgrading the Baikal telescope to the detector NT200+. This detector[2] consists of NT200 and three additional external strings with 12 PMs each at 100 m radius from

NT200, as sketched in Fig. 4. NT200+ has a ν_e-effective volume of 4 Mton at 1 PeV and of 20 Mton at 100 PeV neutrino energies, and allows for precise reconstruction of cascade vertex and energy. The sensitivity limit of NT200+ for a diffuse astrophysical flux of ν_e's, assuming $\gamma = 2$ and a flavor ratio $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at earth, will be

$$E^2 \Phi_{(\nu_e + \bar{\nu}_e)} < 9 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$$

at 90% C.L. and for three years of data.

The NT200+ will be commissioned in spring 2005; in 2004 two outer strings and the upgraded underwater data acquisition system had been installed. For the long-term future, a km^3-scale detector at Lake Baikal is under discussion: made of sparsely instrumented building blocks like NT200+ (with NT200 replaced by a single string).[2]

6. Conclusions

The deep underwater neutrino telescope NT200 in Lake Baikal is taking data since 1998. For the full statistics (April 1998 – February 2003), 372 upward muon neutrino events are found. From the analysis of high energy cascade events we derive a limit on the diffuse flux of astrophysical neutrinos. We demonstrate the capability to set severe constraints for an exotic component in the atmospheric muon flux at PeV energies. In 2005, the upgraded detector NT200+ will start operation[a] and allows to do astroparticle physics at the 10 Mton scale with this largest high energy neutrino telescope in the Northern hemisphere.

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[a] At time of proof-reading, NT200+ had been fully commissioned.